Standard Evaluation Plan
for
Large Hybrid Photovoltaic Inverters

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1.0 INTRODUCTION

The test plan described below is intended to be a thorough evaluation that can be used for the characterization of any hybrid photovoltaic inverter. These inverters are typically three phase. Sandia uses this test plan to evaluate hybrid inverters. Inverters with power outputs between 30 and 300 kilowatts have been evaluated. The purpose of these characterizations is to:

1. provide laboratory acceptance testing for military and other government agency projects
2. benchmark inverter capabilities using a single test methodology,
3. ensure that users have all necessary information required for system design, and
4. identify areas where future development may enhance hybrid systems.

If a test is not applicable, it is omitted and N/A is entered in the appropriate block on the test report. The test reports (Appendix C) are four page documents that report inverter performance. The tests are largely automated and use a National Instruments Labview-based data acquisition system.

2.1 Overview

Prior to testing, the inverter will be configured, checked for functionality, and run at 50% of full load for 30 minutes. The full inverter evaluation (aside from village simulation) can be accomplished in five testing days. The Sandia test configuration uses up to twelve, 48 vdc, C&D flooded lead-acid batteries. Each battery is rated at 1,250 amp-hours at the six hour discharge rate, for a total battery capacity of 720 kWh. Unless otherwise noted, the battery state of charge (SOC) will be > 80% for all tests. This is defined as the "standard" SOC for these tests. All tests will be conducted with batteries and inverters at room temperature.

2.2 Initial Power Cycling

The system initial power cycling will be conducted for a period of 26 hours using resistive loads. The load will begin at 50% of rated power for four hours, continue with a load of 80% of rated power for 20 hours, and conclude with a load of 100% of rated load for 2 hours. Temperatures of the power bridges will be monitored during this test. Infrared photographs are to be taken one hour before the end of this test. Abnormally high temperatures will be noted.

2.3 Direct Current Electrical Evaluation

The dc performance can significantly affect battery lifetime. The intent of this evaluation is to quantify charging efficiency of the power electronics and the level of the dc voltages at which decisions are made. These decisions include generator start/stop and battery equalization start/stop. The battery set-points are generally included in software or firmware inside the inverter and are defined by the battery used in the end application. The test begins with the standard SOC and will place a load of 40% of rated power on the inverter. The batteries are discharged until their voltage is such that the controller commands charging to begin. The charge cycle is monitored until the batteries are fully charged. The float cycle is observed separately. The ability to program set points and provide temperature compensation in the charge algorithm is verified.

The current ripple magnitude for charging current is evaluated while the battery is being finished charged. The dc voltage input range is recorded as the battery is discharged to the battery disconnect level and then recharged to finish charge voltage. The charging efficiency of the inverter power electronics is evaluated for the entire recharge cycle. The parameters of interest are:

- dc ripple at finish charge voltage and in bulk charge mode
- battery low-voltage disconnect voltage
- battery finish-charge voltage
- battery equalize schedule
- charging efficiency of the power electronics
- maximum rate of charge
- battery temperature compensation
- any differences in operation between PV and engine charging.

2.4 Inverter Efficiency Evaluation

System evaluations have shown that the efficiency of systems is often over estimated because the efficiency of small loads and of complex loads is less than that for a large resistive load. The practice of over-sizing inverters to ensure the ability to handle surges results in the inverter being operated at low loads much of the time. The Sandia efficiency evaluation is designed to bound the values of efficiency which are found in field installations. The evaluation includes four categories of inverter loading:

1. resistive loads
2. reactive loads, consisting of inductance and resistance
3. nonlinear loads, consisting of resistance, and nonlinear loads
4. complex loads, consisting of resistance, inductance, and nonlinear loads

Resistive load sweep. The resistive load sweep increases all phases of the inverter load from 0% of rated power to 100% of rated power in approximately ten steps.

Reactive load sweep. The reactive load sweep changes all phases of the inverter load from 10% of rated volt-amps (VA) to 100% of inductive rated VA in approximately ten steps for a fixed power factor (PF). The power factor is changed after each sweep and the test is repeated for PF values of .3, .5, and .7.

Resistive load sweep with fixed nonlinear parallel load. This test places a fixed nonlinear load in parallel with the resistive sweep load. The nonlinear load is applied to a single phase. The nominal nonlinear load consists of a full bridge rectifier that results in 2-pulse nonlinear current. For the purpose of these tests, the resistive sweep is repeated two times with two different values of fixed nonlinear load and terminated when the total VA of the load equals the rated VA of the inverter. The VA of the fixed nonlinear load will be approximately 25%, and 50% of the inverter rated VA. For example if the inverter is rated at 150 kVA, the two values of nonlinear load will be 37 and 75 kVA respectively.

Complex Load Sweep. This sweep places a fixed value of nonlinear load (approximately 50% of rated VA) in parallel with the PF = .5 load from the reactive load sweep. The intent is to plot efficiency for a case that is expected to result in relatively low efficiency. This curve and the resistive curve will bound most of the loads found in practice.

2.5 Load Compatibility Evaluation

Loads that may be difficult for an inverter to support include nonlinear and motor loads. The parameters of interest are:

- voltage regulation
- frequency regulation
- voltage distortion, and
- voltage notching.

The load conditions include full rated load (with motors, nonlinear, or reactive components), peak rated load, block loading, and unbalanced loads (< 3% voltage imbalance desirable).[1]

2.5.1 Performance Parameters

For the loads described in Table 1, 2, and 3, the appropriate steady-state performance parameters are recorded. Voltage and frequency regulation are referenced to the no-load voltage and frequency.

Test Configuration	**% voltage regulation (max)**	**%frequency regulation (V on ϕA)**	**% total harmonic distortion (V on ϕA)**
% full load (PF = 1.0)			
20% full load			
50% full load			
90% full load			
100% full load			
full load (kVA) (RL loading only)			
pf = .5			
pf = .7			
non-linear loads in parallel with R			
NL load = 25% of rated VA, Total VA = 50% load rating			
NL load = 50% of rated VA Total VA = full load rating			
motor loads (x% of inv rating)			
a/c motor only			
a/c motor plus R = 100% load			

Table 1: Steady state voltage regulation, frequency regulation and distortion

[1] ANSI C84.1-95,Appendix D, American National Standard for Electric Power Systems and Equipment-Voltage Ratings (60Hz)

% rating for ϕA/ϕB/ϕC	Load (kW)			% voltage regulation		
	ϕA	ϕB	ϕC	ϕA	ϕB	ϕC
25/25/25						
50/25/25						
100/25/25						

Table 2: Unbalanced linear loads

Block Load	voltage notch amplitude	voltage notch width
from 10% to 90% Resistive	V	ms

Table 3: Block loading

2.5.2 Full load/Overload Capability

The full load/overload tests will evaluate the manufacturer's specification of rated volt-amps and three overloads. These overload tests will be conducted with resistive loads.

Test Configuration	Planned Load Duration	Manufacturer's Specification	Measured Load Duration	Measured Power Level
full load	5 hours			
full load + 20%	15 minutes			
full load + 50%	30 seconds			
full load + 100%	5 seconds			
manufacturer's max power				

Table 4: Full load/overload capability

2.5.3 Motor Loads

The purpose of this test is to determine the ability of the inverter to start motors. The loads are

1. motor only, or
2. inverter fully loaded. A resistive load in parallel with the steady-state motor load is used to fully load the inverter. The value of resistance is selected so that the power dissipated by the resistive load plus the motor VA (at steady state) equals the inverter rated VA.

The transient data is taken when the motors are driving their normal operating mechanical load. Measurements using utility line power are acquired to provide a baseline with which to compare the performance of the inverter.

The three-phase motors available for this testing include

- a 3-hp 120/208 Vac fan motor, 95 A/phase peak surge current, 2,200 watts (pf $\cong$ .83) steady-state, 3 phase power.
- a 7-hp[2] 277/480 Vac air conditioner motor, 82 A/phase peak surge current, 4,800 watts (pf $\cong$ .81) steady-state, 3-phase.
- a large 277/480 Vac air conditioner motor, 275 A/phase peak surge current, 18 kW (pf $\cong$ .78) steady-state, 3-phase power.

[2] Hp value is estimated

- a 10-hp motor loaded with a dynamometer.
- larger motors will be rented as required.

data on motor starting

Sandia's utility-connected starting characteristics for the 10 Hp motor are shown in the table below. For the fully loaded inverter the transient motor load will exceed the specified inverter steady-state load. In the table, the voltage regulation is the steady-state voltage sag divided by voltage before the motor is turned on. Voltage sag is the transient voltage sag during the motor startup divided by the voltage before the motor is turned on. The starting surge is quantified by the peak current and the number of cycles the peak current is required.

Evaluation for the 10 HP air conditioner motor	SNL line motor only	inverter motor only	inverter fully loaded
initial ac voltage (rms)	268.4		
voltage sag	4.6%		
voltage regulation (after sag)	1.1%		
surge current (peak amps)	275.1		
time to steady state (cycles)	11		
steady-state voltage (rms)	265.5		
steady-state current (rms)	29		

Table 5: Motor characteristics (one phase) when started with line power

2.6. Generator Interface

The issues relating to the generator interface are

- voltage perturbations due to voltage source transfer. The acceptable magnitude of voltage notches varies with the robustness of the equipment being powered. The IEEE Emerald Book[3] displays the CBEMA curve; this plot bounds the voltage magnitude and associated time duration of voltage notches which are thought to be a threat to sensitive equipment.
- method of load transfer from inverter to generator. The block loading of a generator with its rated power is generally unacceptable. It is preferred that the inverter transfer load to the generator gradually.
- ability of inverter to track generator frequency. If the load transfer results in a change in the generator frequency, the inverter must be able to track the frequency change, within reasonable limits, until the transfer is successfully completed.
- ability to charge batteries from generator. The inverter must be able to charge batteries from a source on the ac side. It is generally preferred that the inverter fully load the generator by a combination of charging power and load power.
- stand alone capability. If the generator fails, the inverter should support the loads while the battery has adequate charge.

[3] IEEE Emerald Book, "IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment", IEEE, Inc., 1992.

Generator interaction features

UPS function	
Generator start voltage (Low battery)	
Generator stop voltage (max charge battery voltage)	
Generator warm-up time	
Source transfers with rated resistive load	
inverter to generator	
generator to inverter	
Load power to start Generator	
Generator block loading	
Generator utilization	
Generator support	
Equalization parameters	

2.6.1 Evaluation of voltage perturbations during source transfer**.**

The electrical source will be transferred from inverter to diesel and then back again, while the inverter load is at full rated power.

2.6.2 Evaluation of inverter's ability to track the generator frequency.

The purpose of this test is to ensure that the source can be transferred while the load is changing. This test will be conducted with a generator which is sized no larger than the inverter's rated volt-amps. The generator frequency will be changed by repeatedly changing the load from 20% of rated power to 90% of rated power at 2 second intervals. By manual command the source will be transferred from generator to inverter and then back again while the load changes are being commanded. This test will be repeated several times.

2.6.3 Ability to function as a UPS**.**

While the load is being powered by the generator, the generator will be turned off. The turn-on of the inverter and associated perturbations in the voltage waveforms will be observed.

2.6.4 Ability to charge batteries from the generator.

While in the battery charge mode the load will be changed from 10% to 100% of rated load in 10% increments. Full generator utilization will be verified at each load step.

2.6.5 Ability to respond to continuous overloads.

The inverter will be overloaded up to 20%. The ability to start and transfer to the generator (for larger generators) or run in parallel with the generator (for smaller generators) will be observed. If transfer does not occur in 2 minutes the overload will be removed.

2.6.6 Adjustable diesel warm-up time.

After starting, the diesel must be allowed to warm-up prior to being placed on-line.

2.7. Safety

The safety issues relate to the protection of equipment and facility. The following functions will be verified,

a. restrict charging current if battery temperature is unacceptable.

b. emergency shutdown if a fault or out of tolerance condition is observed.

2.8. Simulated Village Test

The inverter will be configured as a component in a simulated village PV power system. The simulated village will have a complex load profile that varies daily. The system will be turned on and left to cycle for up to 30 days.

Appendix A: Terms and Definitions

1. Array Ripple Current. The variation in dc current amplitude; dc ripple current can cause power loss by changing the operating point on an array.
2. Current-source inverter. An inverter circuit in which the switches create an ac current from a dc voltage source[4].
3. Displacement Power Factor. The cosine of the displacement between the voltage and the current at the fundamental frequency.
4. Efficiency. The inverter efficiency is the ratio of the output power to the average dc input power. The efficiency is a function of the dc input voltage and the type of load.
4. Electrical Shutdown. The inverter may be required to automatically shutdown if any of the following conditions occur.
   a. Internal failure
   b. Ground fault (generally refers to a fault> 5 mA.)
   c. A power drain that could result in inverter damage.
5. Tare Power. Power consumed by the inverter with no load
6. Frequency stability. The ability of the inverter to provide a fixed 60 Hz output.
7. Notch[3] "A switching disturbance of the normal power voltage waveform, lasting less than a half-cycle; which is initially of opposite polarity than the waveform, and is thus subtractive from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half-cycle."
8. Power factor (PF). The ratio of true (average) power to apparent power. Primarily of interest because the allowable PF defines the reactive current the inverter must supply. The PF can be measured for 3 cases[5] sinusoidal waveform, dist < 5%, and dist > 5%.

   Case 1: PF = cos θ.

   Case 2: PF = $P/(P^2+Q^2)^{1/2}$ Where $(P^2+Q^2)^{1/2}$ = apparent power (VA), and Q = reactive power (VAR).

   Case *3*: Sometimes referred to as the rms power factor.

$$PF = \left(\frac{V_1 I_1 \cos\theta_a + V_2 I_2 \cos\theta_2 + \ldots\ldots + V_n I_n \cos\theta_n}{\left\{\left(V_1^2 + V_2^2 \ldots\ldots\ldots + V_n^2\right)\left(I_1^2 + I_2^2 \ldots\ldots\ldots + I_n^2\right)\right\}^{1/2}} \right)$$

   where n is a whole integer multiplier of the fundamental frequency, 60 Hz. This expression is sometimes given as PF = W/ (V_{rms} * I_{rms}) where W is the real power.

[4] *Principles of Power Electronics*, J. Kassakian, M. Schlecht, G. Verghese, Addison-Wesley Publishing Company, June 1992.
[5] IEEE Std 1035-1989, "IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters."

9. State of Charge (SOC) Refers to the present battery energy as a percent of battery rating. Full SOC is defined by the manufacturer in an ampere-hour rating. This is the total number of ampere-hours that can be withdrawn from a fully charged battery, usually specified to the maximum depth of discharge and at a specific discharge rate.

10. Surge Power. The peak power, or surge power, is the amount of power that can be supplied to a transient load, such as a motor load, for 3 seconds without interfering with normal inverter operation. The dc voltage input shall be within the manufacturer's specification range.

11. Total Demand Distortion (TDD). The amount of current distortion that a user draws from a utility grid.

12. Total Distortion (TD). Total distortion is a measure of the difference between a pure sine waveform of a specified frequency and a test voltage waveform, usually measured by an audio distortion analyzer. The audio analyzer can filter out the fundamental frequency to obtain the numerator of the total distortion measurement. The measurement includes random noise and other repetitive phenomena, such as slip frequencies, and not just the integer multiples of the fundamental frequency. Thus, TD is always greater than THD. The proliferation of harmonic rich loads on utility circuits, such as adjustable speed drives, lighting ballast's, computers, etc., has led to a stricter revised 1992 IEEE 519. TD is also a function of the input voltage and the type and magnitude of the load.

$$TD = \frac{noise + distortion}{signal + noise + distortion}$$

13. Total Harmonic Distortion (THD). Total harmonic distortion is the ratio of the rms value of the sum of the squared individual harmonic amplitudes to the rms value of the fundamental frequency of a complex waveform. This measurement does not include noise that occurs at non-harmonic frequencies. When specifying THD, it is also necessary to specify the input voltage and the type and magnitude of the load. The THD of the load current is a function of the nonlinear load current profile and other, parallel loads. In general, when nonlinear loads are added in parallel with nonlinear loads, the current THD decreases; however, the voltage THD increases. The addition of even small amounts of resistive load in parallel with a nonlinear load greatly decreases the current THD. The waveforms should be analyzed for harmonic distortion at least to the 50 th harmonic, or 3 kHz for a 60 Hz system. Generally, a spectrum analyzer is used for measurement of total harmonic distortion.

$$THD = \frac{\left(H_1^2 + H_2^2 + \ldots\ldots\ldots + H_n^2\right)^{1/2}}{rms \;\; of \;\; fundamental}$$

14. Rated Power. The amount of power that can be continuously supplied to a resistive load at 25 degrees C, until the unit reaches thermal equilibrium. The rated power is a function of the dc input voltage.

15. Voltage-source inverter. An inverter circuit in which the switches create an ac voltage from a dc voltage source[4].

16. Voltage regulation. The stabilization of output ac voltage against fluctuations in source or load. For a single-phase nominal 120 V ac system–these operating voltages are: no less than 86.7%, no greater than 105.8%, and nominal operating voltage. Also see ANSI C84.1-1995.

Appendix C - Test Report
of the Brand XX Inverter

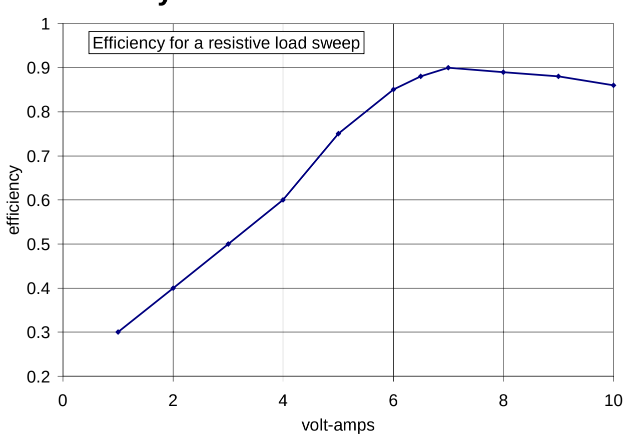
Manufacturer's specifications

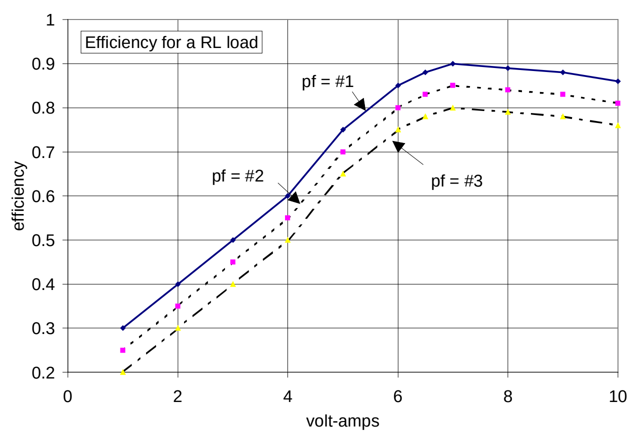
Model Evaluated		Max charge rate	
Rated Power		bulk charge voltage	
Rated volt-amps		taper charge current (Generator stop)	
Surge power		Gen start voltage	
Efficiency		dc low-voltage disconnect	
Nominal dc voltage		Equalization period	
Max dc voltage		Time between equalization periods	
Output voltage (ac)		Output transformer	
Distortion			

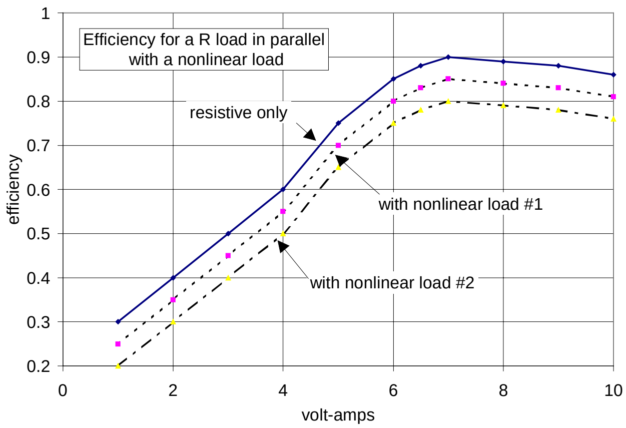
DC evaluation

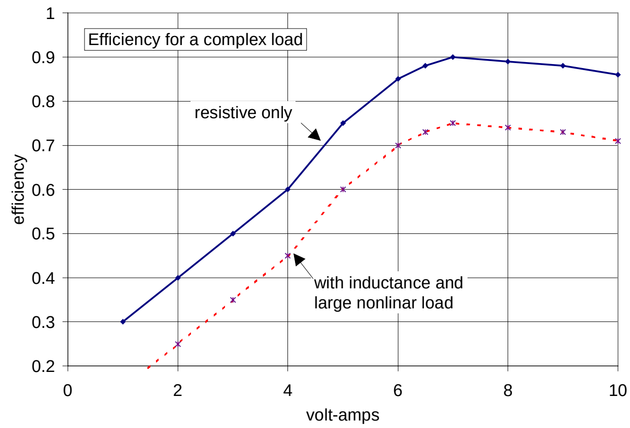
Parameter	**Quantity**
Inverter Mode	
battery disconnect voltage	
Charge Mode	
dc ripple voltage p-p	
dc ripple current p-p	
battery bulk charge voltage	
battery float current (gen stop)	
charging efficiency	

Efficiency






Efficiency for a R load in parallel with a nonlinear load
resistive only
with nonlinear load #1
with nonlinear load #2
efficiency
volt-amps


Efficiency for a complex load
resistive only
with inductance and large nonlinar load
efficiency
volt-amps

Voltage and frequency regulation, and distortion

Test Configuration	% voltage regulation (max)*	% frequency regulation	% total harmonic distortion
% full load (PF = 1.0)			
20% full load			
50% full load			
90% full load			
100% full load			
full load (kVA) (RL loading only)			
pf = .3			
pf = .5			
pf = .7			
non-linear loads in parallel with R			
NL load = 4.4 kVA on phase A Resistive load on all three phases Total Load = 10/6.7/6.7 kVA			
motor loads			
10 hp a/c motor only			
10-hp a/c motor plus 6.4 kW			

unbalanced linear loads

Requested load (kW)	Load (kW)			Vrms		
ϕA/ϕB/ϕC	**ϕA**	**ϕB**	**ϕC**	**ϕA**	**ϕB**	**ϕC**
100%/100%/100%						
100%/80%/80%						
100%/20%/20%						
75%/50%/50%						

Inverter overload

Test Configuration	Planned Load Duration	Measured Load Duration	Measure d Power Level	Blackout?	Generator Start
full load	5 hours				
full load + 20%	10 seconds				
manufacturer's overload					

Motor starting -- 10-hp motor with dynamometer load

	SNL line motor only	inverter motor only	inverter 6.4 kW parallel load in place
initial ac voltage (rms)			
voltage sag			
voltage regulation (after sag)			
surge current (peak amps)			
time to steady state (cycles)			
steady-state voltage (rms)			
steady-state current (rms)			

block loading

Block Load	voltage notch amplitude	voltage notch width
16% to 90% Resistive (4.9 kW to 27 kW)	138 V	

generator interaction features using 30-kVA 277/480V diesel genset

UPS function	
Generator start voltage (Low battery)	
Battery float voltage	
Battery current to stop generator	
Generator warm-up time	
Source transfers with 20-kW resistive load	
inverter to generator-only	
generator-only to charge	
charge to generator-only	
Generator-only to inverter	
Load power to start generator	
Method of loading generator	
Generator utilization	
Generator support	